Accurate estimation of depth of interaction in PET on monolithic crystal coupled to SiPMs using a deep neural network and Monte Carlo simulations

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Abstract– **In PET, the depth of interaction (DOI) information is embedded in the scintillation light distribution sampled by the photodiode array. The block detector can be considered as a non-linear function projecting a beam position coordinate onto a set of photodetector (APD, SiPM) signals. The goal of positioning algorithms is to inverse this mapping and to match the set of photodetector responses with an incident event position coordinate. Furthermore, continuous crystals were investigated as an alternative to pixelated scintillator arrays in positron emission tomography (PET). Monoliths provide good energy, timing and spatial resolution, including intrinsic depth of interaction (DOI) encoding. We propose a method for estimation of the DOI using a deep neural network based on a supervised algorithm. The network was evaluated by Monte Carlo (MC) simulations of a preclinical PET scanner with ten 50×50×10 mm^3 monolithic LYSO crystals and 12×12 SiPM array. All physical phenomena, especially optical interactions, were taken into consideration. The three-dimensional interaction position in each crystal was estimated by the neural network whose inputs were the detection positions on the photodetector plane (X-Y plane) and the deposited energy. Training and validation datasets were generated by the GEANT4 MC toolkit through varying single photons incident direction, angle and energy and readout of the SiPMs output. We used a multilayer perceptron with 4 layers and 256 units as neural network architecture. The optimized layers and units were optimized after comparing several architectures. The spatial resolution in the X-Y plane and Z axis (depth of interaction) were 1.54 and 1.59 mm, respectively. Furthermore, our model was able to predict the DOI below 7 mm depth with a bias under 8.7%. The proposed method enabled higher accuracy of the interaction position estimation than existing methods based on the Anger method. Therefore, estimation of the 3D interaction position based on monolithic detectors is possible using deep neural networks.**

I. INTRODUCTION

EACH coincidence event detected by a PET scanner is linked to a line called line of response (LOR) connecting the two involved detectors. In reality, instead of a LOR we face a volume of response (VOR) which encompasses all possible positions for which the emission of a positron can lead to the absorption of both annihilation photons of the corresponding annihilation pair by the two detector elements. The pursued goal had been the reduction of the VOR to LOR. To accurately estimate the LOR, the interaction positions of each annihilation photon in the crystals should be accurately determined. The use of detectors equipped with monolithic scintillators coupled to a position-sensitive photodetector (APD, SiPM) is a proficient method for 3D position estimation. Having the information about the third dimension or depth of interaction (DOI) reduces the parallax error at off-center positions within a PET ring. Knowledge of the DOI is particularly important for preclinical PET scanners with a small gantry diameter, such as animal imaging devices, dedicated brain PET scanners and female breast devices.

The 3D position of interaction inside the crystal can be estimated based on fitting a model of the light distribution. The maximum likelihood estimation of the interaction position following training is another option that has been successfully implemented [1]. Gonzalez-Montoro *et al.* employed a mathematical expression based on the attenuation of the crystal material and the distribution of the sum of the squared pixel intensities [2]. In this approach, the ratio of the event's energy to the maximum local intensity was utilized as DOI. Besides the above mentioned techniques, other works relied on the use of neural networks to build a lookup table attained by a side irradiation of the crystals [3].

In addition, a 3D interaction position estimation approach based on using artificial neural networks was introduced by Wang *et al*. [4]. Another group developed an estimation method using nonlinear dimensionality reduction to extract features of the detector response [5]. Estimation of the DOI in monolithic crystals faces a number of challenges, including long computational time and skillful calibration. More recently, the Gradient Tree Boosting algorithm was used to extract the scintillation position in monolithic scintillators, achieving a spatial resolution of 2.12 mm [6].

In this work, we evaluate a method for the 3D estimation of the interaction position in monolithic detectors using a deep neural network and Monte Carlo simulations. A number of nonlinear interaction phenomena occur during the scintillation process. Therefore, a neural network was used owing to its ability to model highly nonlinear functions. In addition, we studied the influence of DOI considerations on the performance of a simulated preclinical PET scanner. Moreover, we confirmed the viability for 3D position estimation retrieved by the proposed method compared to Anger positioning logic.

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II. MATERIALS AND METHODS

A. Monte Carlo simulations

Simulation of the whole PET scanner was performed using the Geant4 Monte Carlo toolkit. Optical transportation was taken into account to make the simulation more realistic.

B. Characteristic features of animal PET scanner based on monolithic crystals

We simulated a preclinical PET scanner based on 50.2×50.2×10 mm^3 monolithic crystals coupled to SiPMs (Sensl ArrayC-30035-144P-PCB) with 12×12 array size and 4.2 mm pixel pitch. Image reconstruction was performed based on Anger logic and the proposed positioning algorithms to estimate the position of interaction within the crystals from the distribution of optical photons. Then, a straight line joining the two predicted scintillation positions was assigned as a LOR. All LORs were stored in sinogram format and reconstructed using a version of the OSEM algorithm (OSMAPOSL) implemented within the STIR package (5 iterations and 4 subsets).

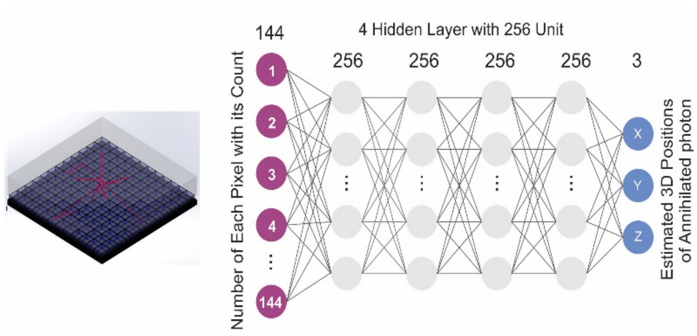

Fig. 1 The network architecture and module schematic diagram.

C. Validation strategy

Simulations were compared with experimental results to validate the MC model. The details of the validation strategy were described in previous work [7].

D. Neural network architecture

The multilayer perceptron (MLP) was used as neural network architecture for estimation of the interaction position in the detector (Figure 1). In this work, several structures of hidden layers and hidden units were evaluated. By considering the position resolution, we have carefully chosen 4 hidden layers and 256 hidden units. For the training step, information about 5×10^6 interactions contain the number of SiPM's pixels (consisting of 144 pixels) fired by optical photons, weight of each pixel and the exact 3D position of the event as ground truth were obtained by MC simulations. Hence, the network was trained to predict the scintillation origin position from the distribution of SiPM's pixels. Thereafter, the input data were transformed into 4 hidden units and 256 units, activated by rectified linear unit (`Relu`). We considered 150 epochs and the Adam method with weight decay of 10^{-4} for optimization and regularization.

The final hidden layer is transformed into 3D position (X, Y, Z)$_{Estimated}$. For testing step, we used 10^6 new interaction data. We used the mean square error (MSE) as loss function. Training was performed on a computer containing a graphics processing unit (NVIDIA Quadra K5200 with 8 GB of memory).

E. Performance evaluation

For performance evaluation, we calculated the spatial resolution for a single detector module and full PET scanner using the NEMA NU4-2008-standards [8] to compare the proposed method with Anger logic.

III. RESULTS & DISCUSSION

In Fig. 2, we present the training and validation loss trend. There is a minor difference between these two parameters, which proves that the network is working properly without any overfitting. Table 1 summarizes the predicted depths (Z) for a single detector module and its corresponding standard deviation (STD) and bias. A scintillation point source was located in 10 positions (depths), 1 mm apart from the SiPM surface to the top surface of the crystal with 1 mm step size. The results indicated that the bias and STDs increase at higher Z (near the entrance surface of the crystal). By increasing the distribution of optical photons on SiPM's pixels, the accuracy of the model for predicting the correct Z value declines. In Fig. 3, the spatial resolution of a point source at six distances from the center of the monolithic module is illustrated. The spatial resolution varies from 0.78 mm to 1.15 mm and from 0.96 mm to 1.6 mm for MLP and Anger logic, respectively. For the PET scanner, we calculated the spatial resolution at five distances from the central axis of the FOV and in two directions (radial and axial) (Fig. 4). Fig. 5 shows the reconstructed images of the image quality phantom when using the Anger Logic and MLP positioning algorithms.

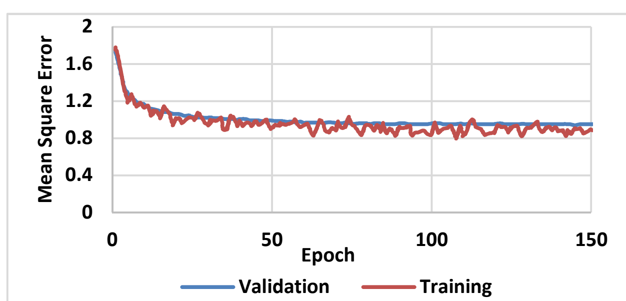

Fig. 2 Plots of training/validation loss curves.

TABLE 1. PREDICTED Z FOR DIFFERENT DEPTHS OF A MONOLITHIC MODULE. THE SCINTILLATION POINT WAS LOCATED AT DIFFERENT Z POSITIONS AS REFERENCE.

Reference Z	1	2	3	4	5	6	7	8	9	10
Predicted Z	1.0	2.0	3.1	4.3	5.3	6.4	7.6	8.6	8.5	8.6
STD	0.3	0.3	0.4	0.6	0.6	1.2	1.6	1.7	1.7	1.7
Bias (%)	3.8	-1.7	2.5	6.4	6.7	6.8	8.7	7.6	-5.8	-14.3

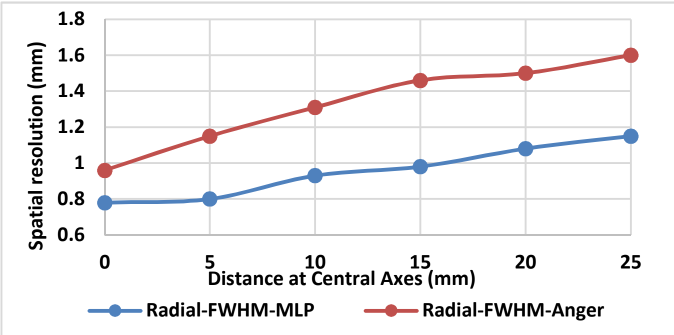

Fig. 3 Spatial resolution of one module for a point source at six distances from the center of the crystal.

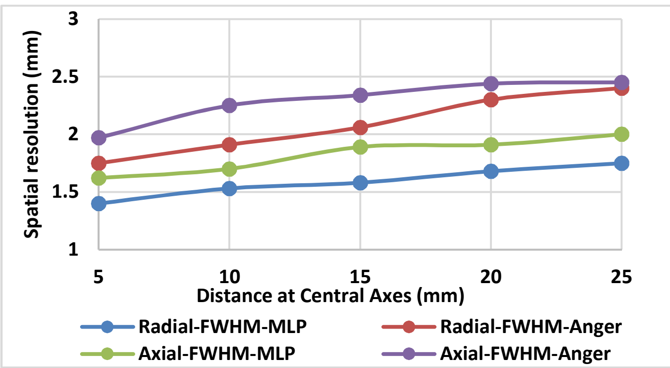

Fig. 4 Spatial resolution of the PET scanner for a point source at five distances from the center of the Z-axis calculated using the NEMA NU-4 protocol.

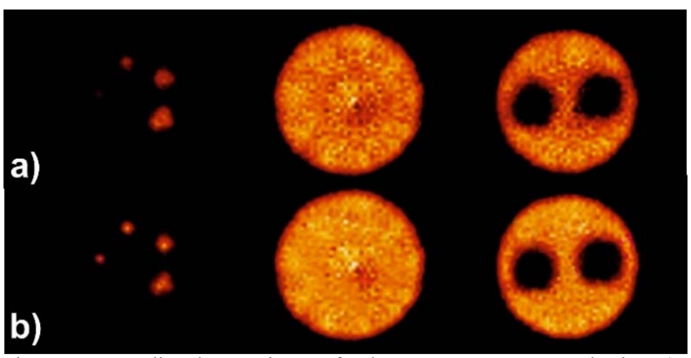

Fig. 5 Image-quality phantom images for the PET scanner generated using: a) Anger positioning logic and b) MLP method.

The proposed algorithm improves the spatial resolution and avoids image distortions compared to conventional Anger positioning algorithm without DOI capability. This improvement is much relevant in the corner of the module and scanner's FOV. To better evaluate the imaging performance, a quantitative evaluation of the spatial resolution was performed. The FWHMs of point sources with different algorithms were derived from image profiles of each point source fitted to a Gaussian. The improvement offered by the novel proposed algorithm is evident, especially for the radial resolution. In this work, Monte Carlo simulations did not consider a number of factors, such as dark noise, cross-talk, after pulsing, photon detection efficiency. This is one of the limitations of this work. The 3D positioning information helps to distinguish the position between the scintillation event and the photon detection by SiPMs, thus improving the coincidence time resolution by taking into account the path traveled by the coincidence photons within the scintillators. The correct time-of-flight can be calculated from the difference in path length between the annihilation position and the scintillation position in each of the coincident detectors.

IV. CONCLUSION

This work showed that extraction of the 3D positional information of annihilation photons inside a monolithic crystal using deep neural networks is feasible. Monte Carlo simulations demonstrated that the proposed method improves position resolution in the XY plane and along the Z axis compared to conventional positioning techniques, such as those based on the Anger logic.

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